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Weighting of environmental trade-offs in CCS—an LCA case study of electricity from a fossil gas power plant with post-combustion CO_2 capture, transport and storage

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Abstract
Purpose Carbon capture and storage (CCS) is increasingly acknowledged as a potent global warming abatement option. It is demonstrated that whilst the global warming potential (GWP) decreases, the other environmental impact category potentials often increase in a life cycle perspective. Despite this, only a few studies clearly address this trade-off or use weighting to compare the positive and negative effects of CCS. The present life cycle assessment (LCA) study focuses, therefore, on presenting several environmental indicators and on weighting the inventory results in order to ascertain which of the analysed systems is to be preferred.
Method The case studied is a projected gas power plant at Tjeldbergodden (Norway), where it is proposed to include post-combustion CCS. Four main scenarios have been analysed, one without and three with CCS. The principal variation between the CCS scenarios is that the steam required for amine regeneration is produced in three different ways: in a separate gas fuelled steam boiler; in a separate biomass fuelled steam boiler; and delivered from the low-pressure steam turbine in the power plant. Design information and technical specifications have been available. The study has used LCA methodology based on the ISO standard 14044, SimaPro 7.3.2.4 software and the Ecoinvent 2.0 database. The functional unit is 1 TWh electricity delivered to the grid. The following environmental impact categories have been included: GWP, acidification potential, eutrophication potential, photochemical ozone creation potential (POCP) and cumulative energy demand (CED). Three weighting methods have been used to ascertain the robustness of the weighting results: ReCiPe, EPS 2000 and IMPACT 2002+.
Results and discussion The characterisation results show that the CCS scenarios have reduced impacts only in the case of GWP. The weighting demonstrates that in the ReCiPe model, climate change is strongly in focus, whilst in EPS 2000, human health and depletion of reserves are dominant. Climate change is also an important factor in IMPACT 2002+, together with effects on human health (respiratory inorganics). The process integration scenario has, however, the best result for all three weighting models. This contrasts with the results from the impact analysis where four of the five analysed impact categories rated the CCS-3 scenario as worse than the reference scenario. One possible option for improving the biofuel boiler scenario is to capture the CO_2 from the combustion of biomass in the external steam boiler. This would not, in all probability, affect the acidification, eutrophication, POCP and CED to any significant degree, but the GWP, and hence the ReCiPe and the IMPACT 2002+, weighting results could be expected to improve.
Conclusions The weighting exercise has identified toxicity as a concern with regard to the biofuel boiler scenarios (CCS-2) and human health issues as having importance for the CCS-3 scenario. It would seem that process integration is a better CCS option than that of CCS providing steam from a separate steam boiler (without CCS), even where this boiler is biomass-fuelled. Any future analysis should focus both on the process integration scenario and the biofuel boiler scenario with CCS of biological CO_2.

Keywords Carbon capture and storage (CCS) · Environmental impacts · Human health · Life cycle assessment (LCA) · Toxicity · Weighting, trade-offs

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1 Introduction

Increasing focus on global warming and its potential effects has led to a growing interest in carbon dioxide capture and storage (CCS) as a promising technology for the abatement of greenhouse gas emissions (Metz et al. 2005; European Commission 2006, 2009; IEA GHG 2010). CCS can be applied to large point sources such as thermal power and heat plants; fuel processing plants; and industrial plants producing metal, cement and chemicals. There are several potential CCS technologies under development (IPCC 2005; IEA 2008; NMA 2010), and the technology of choice for current coal- and gas-fired power plants is post-combustion CO_2 capture using chemicals (amines) as the solvent (IEA 2008). The greenhouse gas emission potential of post-combustion CCS has been well studied, both at the level of power production and on a life cycle basis. Other environmental impacts like acidification, eutrophication, photochemical oxidation and toxicity have not gained as much attention. This is of concern since it has been demonstrated that whilst the global warming potential decreases using CCS, the other impact categories often increase in a life cycle perspective (Veltman et al. 2010; Hertwich et al. 2008; Odeh and Cockerill 2008; Viebahn et al. 2007; Korre et al. 2009; Koornneef et al. 2008; IEA GHG 2006, 2010). Even in studies where the whole life cycle is not taken into account, some emissions are shown to increase (Koornneef et al. 2009, 2010). CCS processes are typical examples of activities where such trade-offs occur. The purpose of the CCS process is to reduce one of the environmental parameters. In order to achieve this, energy is required, which in turn increases the other environmental impact indicators.

In cases where the results differ for different impact categories, the results can be weighted in order to establish which of the impacts are more important for society and to enable the selection of the 'right' technical solution. When the results are not weighted using predefined methods, the author or reader may be tempted to make them easier to understand by placing emphasis on certain impact categories at the expense of others. This could result in an unintentional weighting (Brekke 2012). Analysis showing only one impact category will also lead the reader to believe that this is the whole truth, unless the author(s) underlines qualitatively that other impact categories can be equally important. Several life cycle assessment (LCA) studies of CCS include results for more than global warming (Viebahn et al. 2007; Hertwich et al. 2008; Odeh and Cockerill 2008; Koornneef et al. 2008; Bouvart and Prieur 2009; Veltman et al. 2010; Korre et al. 2010). The greenhouse effect, however, is most often treated as the principal environmental issue. Only a few clearly address the trade-off paradox between these impact categories or focus on the positive and negative effects of CCS, which are being compared (Odeh and Cockerill 2008; Koornneef et al. 2008; Korre et al. 2010). None of these studies use weighting with predefined methods. There is a need, therefore, for comprehensive LCA studies on CCS using acknowledged weighting models.

Whilst there are reasons for using weighting, there are, of course, also motives for not doing so. One of the arguments is that weighting could lead to false conclusions since some of the potentially toxic emissions related to CCS are not yet known. Today, CCS is increasingly acknowledged politically as a potent option for the abatement of global warming (European Commission 2009; WRI 2010; IEA GHG 2010), and several large-scale demonstration plants are being built (OED 2007; IEA 2011) despite the fact that some of the environmental consequences are not yet known. LCA, including the optional weighting step, is thus an important tool in the increasingly holistic nature of the mapping of environmental consequences, more so than the laying of emphasis solely on the global warming potential. If used with care and an awareness of the potential effects of the missing data, the authors believe that weighting could broaden insight with regard to this issue and thus contribute to technological development processes and political decisions at a global level.

The present LCA study focuses on presenting several environmental indicators and on weighting the inventory results in order to see which of the analysed systems is preferable. The case studied is a possible future gas power plant at Tjeldbergodden (Norway), where it is proposed to include CO_2 capture, transport and storage (CCS). The study has been performed for Statoil, and the aim has been twofold: (1) to compare the environmental impacts of different CCS options and thus give useful information regarding improvements in the design of the CCS system and (2) to document the fact that weighting may be necessary when performing LCA of CCS because of the trade-off paradox. In addition, the study questions whether electricity production with CCS is more or less favourable than electricity production without CCS. The functional unit is 1 TWh electricity generated at the Tjeldbergodden gas power plant and delivered to the grid.

2 Methods

2.1 Methodology

The study has been carried out using LCA methodology based on the ISO standard 14044. The following environmental impact categories have been included: global warming potential (GWP), acidification potential, eutrophication potential, photochemical ozone creation potential (POCP) and cumulative energy demand (CED). The impact assessment methods for the different environmental impact categories are based on

the methods found in Table 1. SimaPro 7.3.2.4 software was used together with the Ecoinvent 2.0 database (Frischknecht 2005) in order to carry out the analyses.

Weighting is an aspect of LCA methodology which is useful when the results for different impact categories give contrary indications, thus making it necessary for decision makers to decide which impact categories are more important. Weighting is based on value choices. The methods are based on principles such as distance to target and damage values, as well as combinations of others in monetary or other units. Since weighting never can give an exact answer, the authors have chosen to use three different weighting methods in order to observe the robustness of the weighting results. These weighting methods are described in more detail below (see Section 2.3).

It was decided to include not only the data associated with the environmental impact categories chosen but also all of the identified fundamental input data with regard to emissions and use of energy and other resources. This means that the weighting results can now be used as a control to establish whether potentially important emissions/resources are included in the analysed impact categories. This is also in line with the ICLD handbook (general guide) recommendations (European Commission JRC 2010a). The weighting will not, however, give any indication as to whether fundamental data are missing.

2.2 System description and boundaries

Four scenarios were analysed:

- Reference: Gas power plant without CCS
- CCS-1: Gas power plant with CCS, with a separate gas fuelled steam boiler for amine regeneration
- CCS-2: Gas power plant with CCS, with a separate biomass (wood)-fuelled steam boiler for amine regeneration (four sub-scenarios with different transport modes and distances)
- CCS-3: Gas power plant with CCS. Steam for amine regeneration is delivered from the low-pressure steam turbine in the power plant (process integration).

In all four scenarios, natural gas from the Heidrun field is used in a combined cycle process. The CO_2 capture process is based on post-combustion decarbonisation using monoethanolamine (MEA) absorption. After the capture process, the CO_2 is transported in a 150-km pipeline to storage at the Heidrun licence area. No integration between the CO_2 capture process and the power plant was included in scenarios CCS-1 and CCS-2, except for the electricity consumption in the capture process. This was assumed to be delivered by the gas power plant. These scenarios were assumed to be ‘worst-case scenarios’ for electricity production with CCS at Tjeldbergodden because of the low integration between the power plant and the capture process. In scenario CCS-3, the power plant and the CO_2 capture process are closely integrated by steam delivery from the power plant to the CO_2 capture plant. A simplified flow sheet showing the gas power plant scenarios is shown in Fig. 1.

The power plant is designed with two gas turbines of 262 MW nominal each, in addition to one steam turbine of 328 MW nominal. The net power production will be 832 MW in the reference scenario and 789 MW in scenarios CCS-1 and CCS-2. For scenario CCS-3, the net power produced will be 702 MW. The net efficiency of the power plant is assumed to be 59.1 % in the reference scenario and 44.8 % in the CCS-1 scenario. It is assumed that the CO_2 capture fraction will be 90 %, or 2.1 million tonnes per year. The capture facility will have emissions of CO_2, NO_2, MEA and NH_3, as well as waste containing MEA, which is treated as hazardous. The construction and demolition of infrastructure such as pipelines, platform, terminal, buildings, turbines

Table 1 Impact assessment methods used in this study

Environmental impact category	Impact assessment method	Unit	Comment
Global warming potential (GWP)	IPPC 2007 GWP 100a, V1.02.	kg CO_2 eqv.	
Acidification	CML 2 baseline 2000, V2.05.	kg SO_2 eqv.	
Eutrophication	CML 2 baseline 2000, V2.05.	kg PO_4^{-3} eqv.	Including characterisation factor for MEA developed in this project (0,132 kg PO_4^{-3} -eqv./kg MEA)
Photochemical ozone creation potential (POCP)	CML 2 baseline 2000, V2.05.	kg C_2H_4 eqv.	
Cumulative energy demand (CED)	Cumulative energy demand V1.07 and others.	MJ LHV	In addition, CML 1992 V2.06 is used to get a complete list of characterisation factors (heat values) for all energy carriers included. Corrected for feedstock content

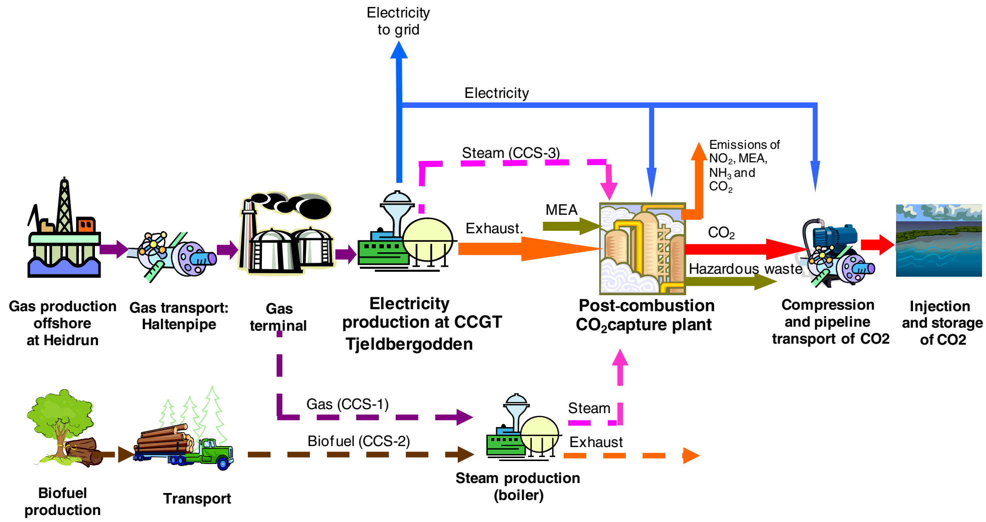

Fig. 1 Simplified flow sheet of the Tjeldbergodden gas power plant case with CO_2 capture, transport and storage (four scenarios)

and process equipment is included in the analysis. The project is documented in Modahl et al. (2009).

2.3 Weighting methods

The three methods used in this study are ReCiPe (based on damage costs: Goedkoop et al. 2009), EPS 2000 (based on willingness to pay: Steen 1999a, b) and IMPACT 2002+ (dependent on damage costs: Jolliet et al. 2008).

2.3.1 ReCiPe

The intended purpose of the ReCiPe method was the consistent combining of midpoint and endpoint methodologies. With the exception of land use and resources, the characterisation factors were calculated on the basis of a cause-and-effect chain. All impacts are marginal (European Commission JRC 2010b). Three different cultural perspectives are used: egalitarian, hierarchist and individualist. In this specific study, the hierarchist average for Europe has been used. In the weighting step, the model uses monetisation on the basis of damage costs.

2.3.2 EPS 2000

The intended purpose of the EPS 2000 method was to assist designers and product developers. In the beginning (1990), it was ahead of its time as it was the first endpoint-based model and the first model which used monetisation. The model uses the precautionary principle, meaning that if a mechanism is uncertain, a most likely case assumption is used. The amount of detail is high, a clear majority of the included models are global, and the time horizon is generally long. Since business-as-usual is the default scenario, resource depletion is given a relatively high damage factor (European Commission JRC 2010b). This model uses monetisation on the basis of willingness to pay for avoiding damage.

2.3.3 IMPACT 2002+

The intended purpose of this methodology was to provide a combined midpoint/damage approach using 14 midpoint categories and the four damage categories human health, ecosystem quality, climate change and resources. The method was developed to enable comparative assessment, and a long-term time horizon was used. As a default, the weighting factors for the four endpoint categories can be taken as being equal, which means that the damage to human health can be compared with the impacts on ecosystems, climate change and resources (European Commission JRC 2010b). The weighting unit in this model is also damage costs, as in ReCiPe.

2.4 Limitations

Despite its holistic approach, the reader should be aware of this study's limitations and data gaps. It should be noted that data from this analysis should not be used for comparison with other studies without carefully having ascertained the system boundaries, assumptions and preconditions.

This analysis has not taken into consideration the following environmental impact categories: ozone depletion potential, toxicity, resource consumption in the form of area consumption, and material consumption and waste. Human activities also have a wide range of impacts on the natural environment, many of which cannot be quantified in terms of kilograms of a given emission or other easily defined units. This analysis does not account for these environmental loads. A list of potentially relevant loads includes: noise, encroachment during construction periods, effects on ecosystems (biodiversity) and ultrasound effects. It should also

be noted that this analysis is an LCA study of a given CCS case, which does not include assessments of the feasibility or practicability of the case, nor the possibility of potential leakages from geological storage. These assessments are performed by other experts with competence in these fields (for example, Hermanrud et al. 2009). In addition, biomass is assumed to be a renewable resource, and nutrition effects caused by the removal of biomass and recycling of ash are not considered.

The use and emission of amine inhibitors, amine promotors and antifoam agents have not been included because of lack of data. The potential degradation products of MEA in the air have also been excluded as, although there is an awareness that these products can have toxic effects, the degradation reactions of MEA are not yet fully understood (Sprenger et al. 2009; Sprenger 2009a, b; Veltman et al. 2010). Experiments are being performed, for example by NILU in Valencia (Sprenger et al. 2009; Sprenger 2009a, b), to establish which degradation products are being produced from MEA, the extent to which they are created and whether they are carcinogenic. Experiments are also being carried out to understand more about the use and emissions of amine inhibitors, amine promotors and antifoam agents (Hagemann et al. 2008). New information will be available as soon as such experiments are documented. The weighting results should therefore be used bearing this in mind.

2.5 Data sources and quality control

Ostfold Research has worked closely with Statoil ASA on this project. Statoil has provided important data and has been responsible for quality control with regard to the conditions, the assumptions and data which have been used, and the results. Design information and technical specifications for the proposed Statoil power plant, capture facilities and CO_2 transport system at Tjeldbergodden have been available for this study (Kvamsdal et al. 2005; Fluor 2005). In addition, the study has made use of data for a future capture facility at Naturkraft's power plant at Kårstø (Svendsen 2006). Literature data from the IEA Greenhouse Gas R&D programme and Statistics Norway have also provided useful information (IEA GHG 2006; Hoem 2006). Some of the most important design information and technical information used in this study is summarised in Table 2.

3 Results

3.1 Characterisation results

The characterisation results are presented in Table 3. The corresponding relative impacts for the different power plant scenarios are shown in Fig. 2. A clear trend shows that the CCS scenarios have reduced impacts only for the category global warming potential. The total reduction in CO_2 equivalent emissions is 47 % for the CCS-1 scenario (gas boiler), 71–76 % for the CCS-2 scenarios (biofuel boiler) and 77 % for the CCS-3 scenario (process integration) when compared with the reference scenario. The impacts for the CCS scenarios are higher than for all the other impact categories analysed in the reference scenario. These results are in line with the LCA results found in the literature pertaining to electricity production with CCS (Veltman et al. 2010; Bouvart and Prieur 2009; Koornneef et al. 2008; Hertwich et al. 2008; Odeh and Cockerill 2008; Viebahn et al. 2007). This effect is caused by several factors. Emissions from the capture process itself (ammonia, MEA and acetaldehyde) contribute, as do the efficiency penalties incurred through the consumption of electricity during the CO_2 capture process. These penalties also apply to the compression and pipeline transport of CO_2, meaning that more gas is required for the production of the same amount of electricity supplied to the grid. Another factor is the withdrawal of low-pressure steam used in regenerating the solvent in scenario CCS-3, and, thus, the loss of thermal work in the power plant. The production, transport, treatment and combustion of gas (scenario CCS-1) and biofuel (scenario CCS 2a/b/c/d) during the production of steam for amine regeneration also have an effect. With regard to the impact categories, acidification, eutrophication, POCP and CED, the principal difference between scenario CCS-1 and the four CCS-2-scenarios is that created by the transport of biofuel. The least damaging CCS scenario for these four impact categories is scenario CCS-3.

Construction of the infrastructure, including production of materials and the waste treatment of these at their 'end-of-life' is shown to be generally insignificant, both for the reference and CCS scenarios. This is in line with findings for previous fossil fuel systems, e.g. Askham et al. (1998), Frischknecht (2007), Koornneef et al. (2008) and Bouvart and Prieur (2009). Compression, pipeline transport, injection and storage of CO_2 also have almost negligible impacts for all of the impact categories analysed.

3.2 Weighting results

The weighting results are shown in Figs. 3, 4 and 5. Only two of the CCS-2 scenarios are shown because of similarities in the results.

3.2.1 Results from the ReCiPe weighting model

In the ReCiPe weighting model, the best result (lowest score) is achieved by scenario CCS-3, followed by the CCS-2 scenarios, which are 39–84 % higher, and scenario CCS-1 (104 % higher). The reference scenario score is more

Table 2 Summary of design information and technical specifications used

Parameters			Units	Reference scenario	Gas boiler CCS-1 scenario	Biomass-fuelled boiler CCS-2 scenario	Process integration CCS-3 scenario
Fuel	Flow rate	Fossil gas	kg/s	30.2	37.8	30.2	30.2
		Biomass (wet basis)	kg/s	–	–	74.5	–
		Biomass	fm^3/s	–	–	0.1	–
	Chemical energy (LHV)	Fossil gas	MW	1,407	1,761	1,407	1,407
		Biomass (effective heat value)	MW	–	–	354	–
		Biomass (dry matter/ theoretical heat value)	MW	–	–	857	–
Other resources	MEA consumption		kg/s	–	1.11E−01	1.11E−01	1.11E−01
	Activated carbon consumption		kg/s	–	4.17E-−03	4.17E−03	4.17E−03
Steam to amine regeneration	Flow rate		kg/s	139	139	139	139
	Energy content		MW	301	301	301	301
Power output	Gas turbines		MW	524	524	524	524
	Steam turbine		MW	328	328	328	242
Power used	Auxiliaries and steam cycle pumps		MW	20	20	20	20
	Capture process, compression and storage		MW	–	43	43	43
Nett output (to grid)	Power		MW	832	789	789	703
	Annual energy production		TWh/year	6.7	6.3	6.3	5.6
Nett efficiency[a]	Based on the effective energy in biomass		%	59	45	45	50
	Based on the theoretical energy in biomass		%	59	45	35	50
CO_2 capture of exhaust from power plant	Capture fraction		%	90	90	90	90
	Capture flow rate		kg/s	–	74.2	74.2	74.2
			tonne/year	–	2,136,000	2,136,000	2,136,000
Emissions to air from power plant/capture facility[a]	Flow rate of…	CO_2	kg/s	82.3	8.0	8.0	8.0
		H_2O	kg/s	64.7	81.1	81.1	81.1
		SO_2	kg/s	–	–	–	–
		NO_x	kg/s	1.0E−02	1.0E−02	1.0E−02	1.0E−02
		CH_4	kg/s	3.2E−02	3.2E−02	3.2E−02	3.2E−02
		NMVOC	kg/s	8.5E−03	8.5E−03	8.5E−03	8.5E−03
		CO	kg/s	6.0E−02	6.0E−02	6.0E−02	6.0E−02
		$PM_{2.5}$	kg/s	4.3E−03	4.3E−03	4.3E−03	4.3E−03
		POP-PAH ex PAH 6 and 4	kg/s	5.0E−07	5.0E−07	5.0E−07	5.0E−07
		POP-PAH 4[b]	kg/s	0.0E+00	0.0E+00	0.0E+00	0.0E+00
		POP-PAH 6[c]	kg/s	3.2E−08	3.2E−08	3.2E−08	3.2E−08
		Dioxin	kg/s	1,8E−12	1.8E−12	1.8E−12	1.8E−12
		Pb	kg/s	8.9E−09	8.9E−09	8.9E−09	8.9E−09
		Cd	kg/s	7.1E−08	7.1E−08	7.1E−08	7.1E−08
		Hg	kg/s	3.6E−08	3.6E−08	3.6E−08	3.6E−08
		As	kg/s	1.4E−07	1.4E−07	1.4E−07	1.4E−07
		Cr	kg/s	7.5E−07	7.5E−07	7.5E−07	7.5E−07
		Cu	kg/s	5.7E−07	5.7E−07	5.7E−07	5.7E−07
		NH_3	kg/s	–	6.26E−03	6.26E−03	6.26E−03

Table 2 (continued)

Parameters			Units	Reference scenario	Gas boiler CCS-1 scenario	Biomass-fuelled boiler CCS-2 scenario	Process integration CCS-3 scenario
			ppmv	–	8	8	8
		MEA	kg/s	–	1.04E−02	1.04E−02	1,.4E−02
			ppmv	–	4	4	4
		Acetaldehyde	kg/s	–	1.09E−02	1.09E−02	1.09E−02
			ppmv	–	5.5	5.5	5.5
Emissions to water from capture facility[a]	Flow rate of…	NH_3	kg/s	–	2.82E−03	2.82E−03	2.82E−03
Waste from capture facility[a]	Flow rate of…	Reclaimer waste	kg/s	–	0.237	0.237	0.237

[a] This table shows a selection of emissions, waste and used energy from the power plant/capture facility only. Along the value chain for producing electricity, there are emissions and waste, and energy is used in several other facilities and equipment also

[b] PAH 4 is also referred to as LRTAP and includes the following components: benzo(*a*)pyrene, benzo(*b*)fluoranthene, benzo(*k*)fluoranthene and indeno(1,2,3-cd)pyrene (Finstad et al. 2001)

[c] PAH 6 is referred to as Borneff-6 and includes the following components: benzo(*a*)pyrene, benzo(*b*)fluoranthene, benzo(*k*)fluoranthene, indeno (1,2,3-cd)pyrene, fluoranthene and benzo(*ghi*)perylene (Finstad et al. 2001)

than 2.5 times higher than the best scenario. Despite the fact that four of the five analysed impact categories rated all the CCS scenarios as being worse than the reference scenario, the ReCiPe method weights the CCS scenarios as less burdensome in total. In scenario CCS-3, the main contributing factor in the weighting result is climate change (78 % in total), but fossil depletion (11 %) and particulate matter formation (10 %) also play an important role. The impacts of fossil depletion and particulate matter formation are even greater in the biofuel boiler scenarios, 13–18 % and 18–20 %, respectively. Here, human toxicity is also clearly visible (6–8 %). The weighting result for the reference scenario is totally dominated by climate change (96 % in total).

The contribution of particulate matter formation to the weighting results in the ReCiPe model is largely due to combustion processes (wood and gas, including emissions from shipping operations). However, the production of monoethanolamine also plays a minor role (CCS-3), whilst human toxicity contributions are due in the main to wood ash handling (CCS-2).

Table 3 Impact assessment results for the analysed power plant scenarios

Scenarios	Global warming potential (tonne CO_2 eqv./TWh, g CO_2 eqv./MWh)	Acidification potential (tonne SO_2 eqv./TWh, g SO_2 eqv./MWh)	Eutrophication potential (tonne PO_4^{3-} eqv./TWh, g PO_4^{3-} eqv./MWh)	Photochemical ozone creation potential (tonne C_2O_4 eqv./TWh, g C_2O_4 eqv./MWh)	Cumulative energy demand (TWh LHV/TWh, kWh LHV/kWh)
Reference scenario	395,220	148	28.1	54.0	1.84
Scenario CCS-1 (gas boiler)	208,220	275	68.0	101.4	2.57
Scenario CCS-2a (biofuel boiler)	94,573	378	104.2	114.7	2.46
Scenario CCS-2b (biofuel boiler)	108,216	453	123.7	131.6	2.53
Scenario CCS-2c (biofuel boiler)	100,251	542	120.1	125.0	2.49
Scenario CCS-2d (biofuel boiler)	114,219	806	151.1	146.8	2.55
Scenario CCS-3 (process integration)	90,666	239	62.1	101.5	2.20

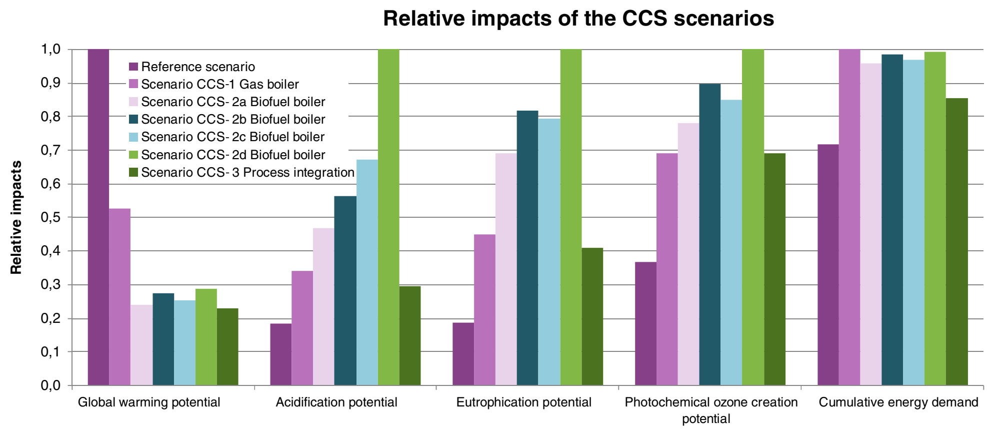

Fig. 2 Relative impacts of the CCS scenarios in relation to the reference scenario

3.2.2 Results from the EPS 2000 weighting model

In the EPS 2000 weighting model, the best result (lowest score) is achieved by scenario CCS-3, followed by scenario CCS-1, which is 58 % higher. The weighting score for the reference scenario is 99 % higher than the best scenario (CCS-3), whilst scenarios CCS-2a and CCS-2d are 108 and 140 % higher, respectively. Despite the fact that four of the five analysed impact categories rates all the CCS scenarios as worse than the reference scenario, the EPS 2000 method weights two of the CCS scenarios as being less burdensome in total. In contrast to the ReCiPe weighting method, EPS 2000 does not weight the reference scenario as the worst case.

In the case of all the scenarios, except CCS-3, the principal contributors to the EPS 2000 weighting results are the effects on human health in the form of (severe) morbidity and life expectancy (61–82 %). The second largest contributor is the depletion of reserves (18–39 %). In the case of scenario CCS-3, the rating for the depletion of reserves is slightly larger than that for the effects on human health (54 vs. 46 %). The high value in the category for depletion of reserves is due to the extraction of fossil gas and the production of steel. The results within the categories morbidity, severe morbidity and life expectancy categories (human health) are largely due to emissions from the combustion of gas (all scenarios), the combustion of biofuel (the CCS-2 scenarios) and the CO_2 capture process (CCS-3).

Whilst climate change is most important in the ReCiPe weighting method, EPS 2000 has a stronger focus on human health and the depletion of resources.

3.2.3 Results from the IMPACT 2002+ weighting model

The best result (lowest score) in the IMPACT 2002+ weighting model is achieved by scenario CCS-3. This is followed by CCS-1, which is 75 % higher, and CCS-2a (115 % higher). The score for scenario CCS-2d and the reference scenario are almost the same, being 168 and 176 % higher than scenario CCS-3, respectively. Despite the fact that four of the five analysed impact categories rated all of the CCS scenarios as being worse than the reference scenario, the IMPACT 2002+ method weights only one of the CCS scenarios as being more burdensome than the reference.

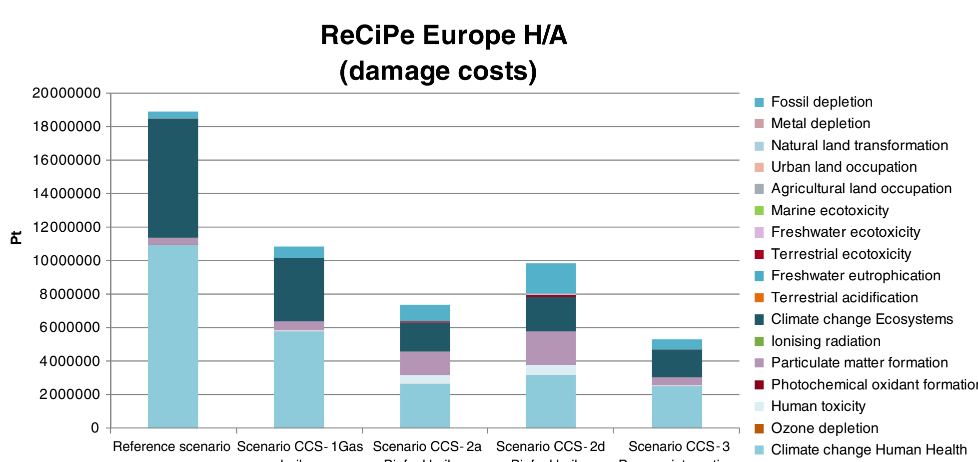

Fig. 3 Weighting results for the ReCiPe model

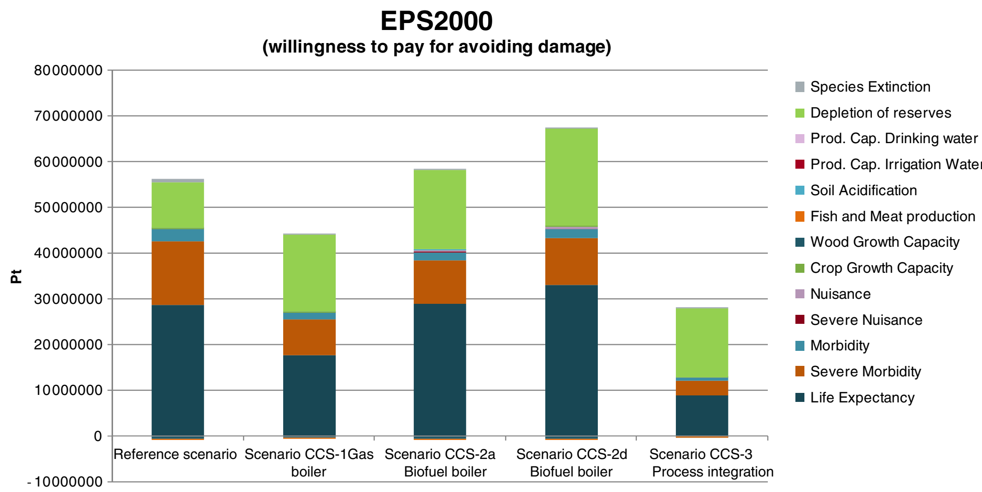

Fig. 4 Weighting results for the EPS 2000 model

IMPACT 2002+ does not weight the reference scenario as the worst case. This is similar to the EPS 2000 weighting method.

In the case of all the fossil-based scenarios (reference scenario, CCS-1 and CCS-3), the principal contributor to the IMPACT 2002+ weighting result is that of global warming potential (53–87 %), followed by the category respiratory inorganics (10–37 %). In CCS-2 scenarios, respiratory inorganics are most important (54–55 %), leaving global warming at 24–25 %. Here, it can also be seen that ecotoxicity (terrestrial) plays a role (8–10 %). Use of non-renewable energy contributes to 2–10 % in all the scenarios.

The scores for respiratory inorganics are due in the main to combustion processes (gas and biofuel), transportation of biofuel (CCS-2) and the CO_2 capture process (CCS-3). The scores for terrestrial ecotoxicity in CCS-2a and CCS-2d are principally due to the disposal of wood ash.

Climate change is a significant factor when IMACT 2002+ is applied to the studied scenarios, and the same may be said for ReCiPe. Respiratory inorganics are also important in IMPACT 2002+, just as the effects on human health have a strong focus in EPS 2000.

4 Discussion

The characterisation results show clearly differing trends, proving the advantages of applying weighting. When comparing the results from the three weighting models used in this study, there are two significant differences:

- With ReCiPe, the result for the reference scenario is clearly the worst alternative of the studied options. In addition, all the CCS-2 scenarios are better than scenario CCS-1. With EPS 2000 and IMPACT 2002+, the scores

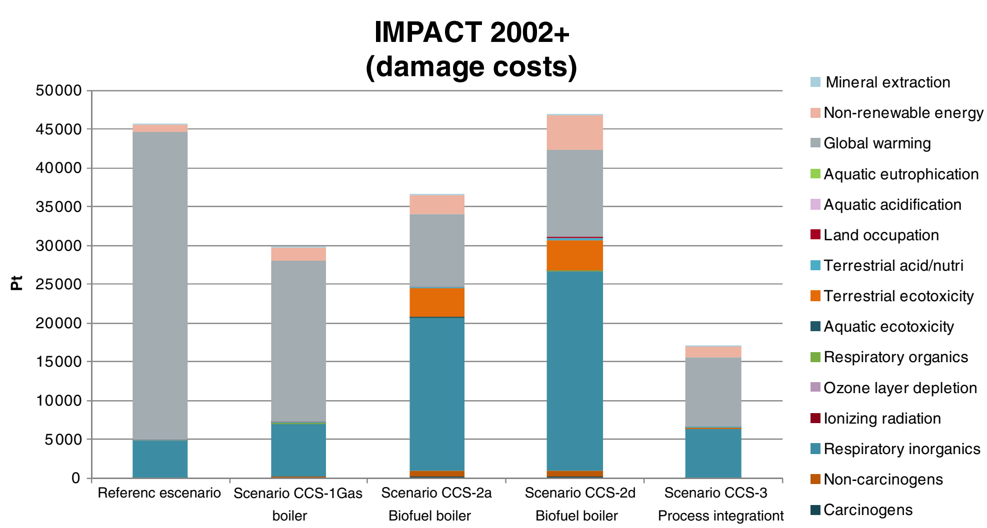

Fig. 5 Weighting results for the IMPACT 2002+ model

for the CCS-2d scenarios are higher than both the reference scenario and CCS-1.

- In ReCiPe, there is a strong focus on climate change, whilst in EPS 2000, human health and the depletion of reserves are dominant. Climate change is also important in IMPACT 2002+, as are the effects on human health (respiratory inorganics).

There are also some significant similarities:

- Scenario CCS-3 has the lowest score, and thus the best result, for all three weighting models used in this study. This contrasts with the results from the impact analysis, where four of the five analysed impact categories rated the CCS-3 scenario as worse than the reference scenario.
- Both EPS 2000 and IMPACT 2002+ indicate the CO_2 capture process as being potentially important with regard to human health (in the form of life expectancy and morbidity in EPS 2000 and as respiratory inorganics in IMPACT 2002+).
- It can be seen that, to some extent, toxicity makes a contribution in the CCS-2 scenarios in both ReCiPe and IMPACT 2002+.

Emissions from the transport and combustion of biofuel, in addition to wood ash handling, make the characterisation and weighting results for the CCS-2 scenarios less favourable than those for the CCS-3 scenario. One possible option for improving the CCS-2 scenarios is to capture the CO_2 from the combustion of biomass in the external steam boiler. This would, in all probability, have little effect on the acidification, eutrophication, POCP and CED, but the global warming result, and hence the ReCiPe and the IMPACT 2002+ weighting results, would be likely to improve.

The authors of this study have chosen to exclude impact categories concerning toxic effects because of the high degree of uncertainty regarding toxic emissions in the input data material. All the input data are included in the weighting, not only the data associated with the environmental impact categories chosen. The study has used weighting to investigate whether or not toxicity could be a subject of major concern in CCS systems. This is in line with the recommendations in the ICLD handbook (general guide) for checking whether potentially important emissions/resources are included (European Commission JRC 2010a). The results of the weighting exercise have shown that toxicity makes a contribution in some of the scenarios (CCS-2) in two of the three weighting models used. This is despite data gaps on this issue in the current life cycle inventory data set. It is also acknowledged that the degradation reactions from the emission of MEA can have toxic effects (Sprenger et al. 2009; Sprenger 2009a, b). This shows that toxicity ought to have a stronger focus in future data gathering and impact analyses of CCS systems. In the case of scenario CCS-3, it is important to take into consideration that the CO_2 capture process has been shown to have significance for human health issues (life expectancy and morbidity in EPS 2000 and respiratory inorganics in IMPACT 2002+).

Since the missing data materials are approximately the same for all the CCS scenarios analysed, weighting can still be used to compare the different CCS options. The weighting exercise gives a broader perspective and enables the identification of some important aspects. Characterisation alone would not do this. This shows that local issues (toxicity and human health issues) can still have an importance for the development of a technology for the abatement of a global environmental problem. Since ethical and idealogical values are involved in weighting, there will never be consensus on these values (Baumann and Tillman 2004). There are many cases internationally which underline the importance of local, political issues, and risk perception is of vital importance to decision making for CCS. Terwel et al. (2011) write that competence is not as important as public perception of the motives for public acceptance. There are several recent examples of local issues preventing the development of full-scale CCS in Europe. In the Netherlands, Germany and Denmark, the fear of irreversible changes which could arise from storage leaks (on land) have been important issues in the decision making which has stopped these projects (Guardian 2011; ICIS Heren 2011; Zero 2011). Concerns about local toxic emissions from the post-combustion capture technology have been important in Norway (TU 2011). This would imply that a weighting model attaching significant weight to human health effects could be appropriate in Norway. The Global CCS Institute (2011) describes a public engagement approach as being important in order to identify and mitigate potential challenges. This is because public engagement is situation- and site-specific. It can thus be seen that politicians and decision makers face a very real exercise in understanding these issues and in assigning values to their relative importance both locally and globally. The weighting exercise identifies climate change and human health as potentially important considerations, although the issue of the perception of risk in relation to storage is not included.

5 Conclusions

The weighting exercise has identified toxicity as a matter of concern for the biofuel boiler scenarios (CCS-2) and human

health issues such as life expectancy, morbidity and respiratory inorganics as having significance for the CCS-3 scenario. It can therefore be seen that the data arising from experiments which are currently underway to fill in the gaps in data, with regard to chemicals and degradation products of MEA, are likely to be important. Thus, it should be noted that the absolute weighting results in this study must be used with care. It is not possible at this point to draw a conclusion as to whether electricity production with CCS is more or less favourable than electricity production without CCS. It is, however, still possible to use this weighting in comparing the various CCS options and as a control when checking whether potentially important emissions/resources are included in the impact categories analysed. Both the characterisation results and the weighting show that process integration (CCS-3) is a better CCS option than CCS providing steam from a separate steam boiler (without CCS), even when this boiler is fuelled with biomass. The weighting exercise has also shown that issues of human health are possibly important for CCS.

6 Recommendations

LCA, including weighting, is an important tool for assessing different designs and configurations in the case of post-combustion CCS, where the results of the varying environmental impacts tend to diverge. The full benefits of weighting can be realised in further work, which will fill the important data gaps identified in this paper.

Missing data with regard to degradation products from MEA and emissions of amine inhibitors, promotors and antifoam agents should be included in future analysis of CCS systems. This would make the weighting exercise even more relevant, making it possible to compare the production of electricity with CCS with its production without and including more areas of public and regulatory concern. Several weighting models should be used.

It is important to continue the search for more optimal design options in the CCS system. There should be focus on the CCS-3 scenario (process integration) since this has been proven to be the best of the CCS scenarios analysed. There should also, however, be an analysis of the CCS-2 (biofuel boiler) with capture of the biological CO_2 in the flue gas from the external steam production, even if this scenario is found not to be economically feasible today (Mathiesen et al. 2008). One obvious way of reducing the environmental effects from the CCS systems, regardless of which CCS scenario is chosen, is the reduction of both the efficiency penalty and the consumption of steam for regenerating amines as well as of the emissions of MEA, ammonia and acetaldehyde.

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